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Using digital geologic maps to assess alluvial fan flood hazards

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INTRODUCTION

The factors that make alluvial fans desirable for development – relatively planar slopes, good surface drainage characteristics, and excellent views – are the result of natural processes such as floods and debris flows, which can negatively affect lives and property. Currently, alluvial fan floodplains are mapped by the Federal Emergency Management Agency (FEMA), in coordination with local flood control agencies where communities participate in the National Flood Insurance Program (NFIP). However, FEMA mapping is rarely conducted in undeveloped areas, and therefore, alluvial fan flood hazard information is often unavailable for long-term planning.

The California Geological Survey (CGS) served as a technical consultant to the Alluvial Fan Task Force (AFTF), an inter-agency, multi-disciplinary effort that provided planning and flood control departments with guidelines for minimizing loss of life and property while also preserving beneficial resources on alluvial fans. As part of this effort, CGS proposed an approach for land use planners that may be used to establish a preliminary site assessment in the absence of FEMA flood hazard data. The approach includes integrating digital Quaternary geologic map data with first-order alluvial fan flood hazard assessments, resulting in derivative maps showing: (1) areas that are underlain by Quaternary sediments that may include alluvial fans; and (2) the relative magnitude of alluvial fan flooding hazards. The flood hazard map is supported by a proposed methodology for determining the relative hazard. These two map products are designed to assist landowners, developers, regulators, and the public in identifying those areas where quantitative studies are likely to document an alluvial fan flood hazard. By characterizing potentially hazardous areas, the maps are intended to promote best practices in land use and floodplain management.

Background

Alluvial Fan Flooding

Alluvial fans form where streams emerge from mountain fronts onto relatively flat valley bottoms. Within a mountain range, particularly in areas experiencing tectonic uplift, a stream is often steeply inclined and confined to a single channel by narrow canyon walls. Once a stream reaches the mountain front, its gradient typically flattens and waters may spread into a distributary network of channels below the apex of the fan, both of which reduce the depth and velocity of stream waters and reduce size and volume of sediment that the stream is capable of carrying. It is this change in gradient and confinement that results in conditions where sediment builds up into the characteristic fan-shaped pattern of an alluvial fan. During a major flood, waters can entrain sediment as a hyperconcentrated flood (debris flood; Pierson and Costa, 1987), where roughly 20 to 60 percent of the volume is sediment and debris. They may also evolve into a debris flow, where over 60 percent of the flow volume is sediment and debris. The interplay between these processes is exacerbated by channel instability, where banks between adjacent channels (interfluves) are relatively low, and are susceptible to failure, by the rise in the channel base from sediment deposition from hyperconcentrated floods and debris flows (aggradation), and by overland flow on adjacent surfaces that create small side channels heading into these unstable areas (Field, 2001). These processes lead to avulsion - the sudden cutting off of an existing channel, and the formation of new channel that diverts part or all of the flow. On relatively lower gradient fans, such as those in Arizona that have been used to characterize avulsive processes (Field, 2001), a relatively longer time may be required for these processes to occur than for higher gradient and geomorphically active fans common in southern California that are dominated by debris flow processes (NRC, 1996; Pelletier and others. 2005). This is because on a debris fan, a single debris flow deposit may block a shallowly incised channel after one rainfall event, so that in subsequent events flow is immediately diverted to a new channel. In contrast, multiple events may be required to sufficiently raise a channel base on a water flood dominated fan, or to cause side channel incision into a main channel such that avulsions occur in the next rainfall event.

After numerous flooding events on alluvial fans resulting in repetitive losses to life and property, FEMA sought to better define the hazard as, "…flooding occurring on the surface of an alluvial fan or similar landform which originates at the apex and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and, unpredictable flow paths" (FEMA, 2003). FEMA has formally recognized that modeling this type of flooding is significantly different than riverine-type flooding, and requires a cooperative effort between geologists and engineers.

Types of Alluvial Fans

The type of alluvial fan and mode of deposition, whether it is built up from hyperconcentrated flows, debris flows, or both, will differ with geologic setting. Factors that influence the mode of deposition are rainfall frequency/intensity, tectonic activity, upland watershed relief, channel slope, vegetation, and lithology and structure (erodibility) of bedrock in the upland watershed that is the source of sediment. For assessment purposes, alluvial fans are subdivided into three types based on their principal style of flooding and sedimentation: Streamflow fans (figure 1), Debris flow fans (figure 1), and Composite fans (Bull, 1977; and NRC, 1996). These are discussed below.

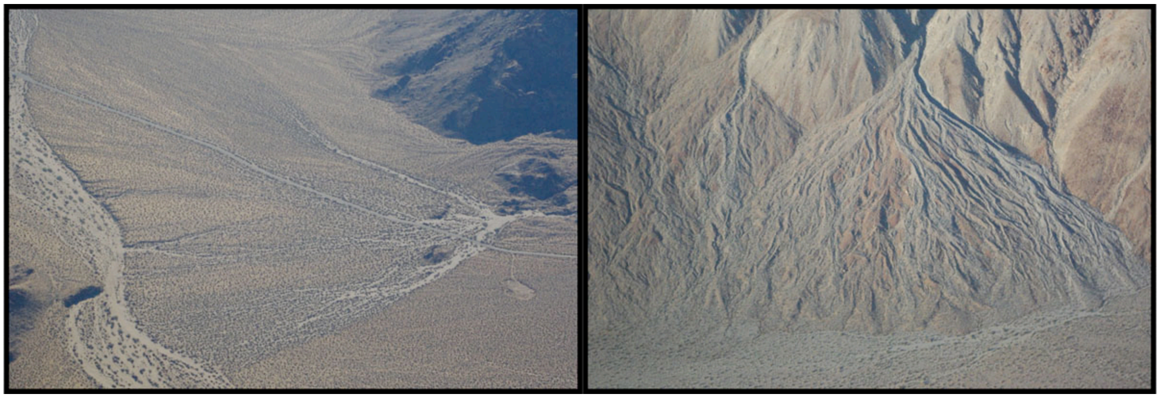

Figure 1. Left side shows a streamflow fan, in Riverside County, California. Right side shows a debris flow fan, in San Diego County, California.

Streamflow fans -- alluvial fans that were built-up through successive water floods with sediment by volume concentrations that may reach into hyperconcentrated thresholds. Slopes on streamflow fans are generally less than 3-4 degrees, which is considered to be the threshold between streamflow fan deposition and debris flow deposition (Jackson, et, al., 1987). Stream channels on streamflow fans have large width-to-depth ratios and are typically braided. Erosion and deposition can alter channel flow during a single flood event (NRC, 1996) where deposition occurs as bars along the margins or center of the channel.

Debris flow fans -- alluvial fans that were built-up through successive hyperconcentrated, transitional, and debris flow events (Keaton and Lowe, 1998; Staley and others, 2006). Slopes on debris flow fans may be as steep as 6 to 8 degrees (or greater), and may have terminal lobes, marginal levees and trapezoidal or U-shaped channels with relatively low width-to-depth ratios. Deposition is episodic, and rapid aggradation or plugging may occur in much deeper channels than is the case for stream flow fans. Even channels that appear to be stable during flood events may be subject to avulsion during or after debris flow, and this contributes to the uncertainty in down-fan flow direction typical for alluvial fans.

Composite fans -- alluvial fans that were built-up through water floods, hyperconcentrated flows, transitional flows, and debris flows and contain features found on both stream debris flow fans and debris flow fans. Slopes on composite fans typically range from 4-8 degrees (Jackson and others, 1987). In general, the proximal portions of the fan consist of coarse debris flow deposits that are interlayered with hyperconcentrated flow deposits. Stratified finer-grained flood deposits are distributed randomly, but with higher concentrations at the distal portions of the fan. Proximal areas typically contain rough surfaces as apparent on aerial photographs and detailed topographic maps (Giraud, 2005).

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AFTF DERIVATIVE DIGITAL GEOLOGIC MAP PRODUCTS

Alluvial Fan Footprint Advisory Map: An Alluvial Fan Screening Tool

For the benefit of the land-use planner, maps that indicate areas underlain by alluvial fan sediments (figure 2) provide information about the potential for a proposed development to be located where alluvial fan flooding may occur, indicating a need for additional studies. These advisory maps of Quaternary-age alluvial fan deposits are based on digital surficial geologic maps by the CGS and the USGS, and are being compiled at 1:100,000 (100k) for the 10-county southern California AFTF region (Kern, Los Angeles, San Diego, Santa Barbara, San Luis Obispo, San Bernardino, Riverside, Imperial, Orange, and Ventura).

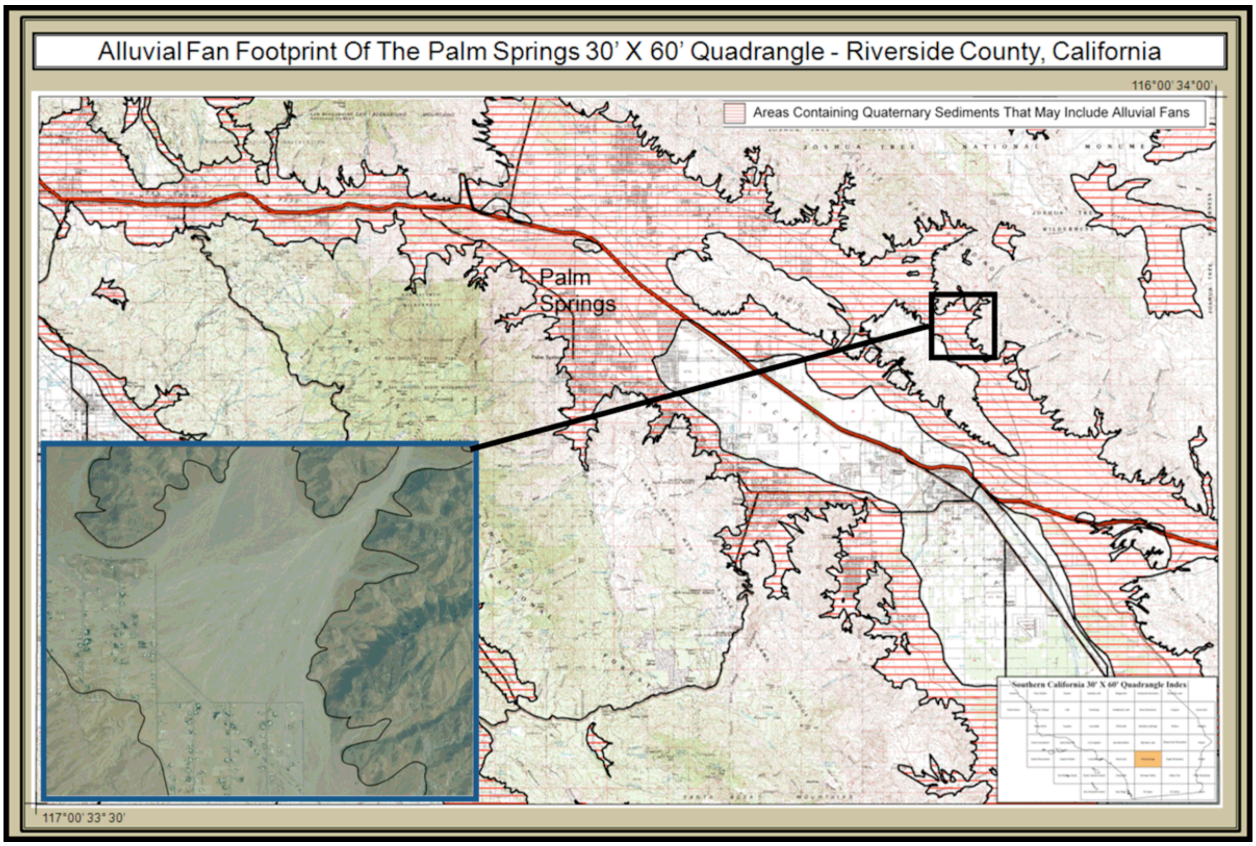

Figure 2. Alluvial fan footprint advisory map of a portion of the Palm Springs 100k quadrangle. Inset figure shows digitized extent of Quaternary-age alluvial fan deposits drawn on 2005 NAIP imagery.

Derivation of Alluvial Fan Footprint based on Existing Digital Data

Areas underlain by Quaternary-age alluvial fans that may be subject to alluvial fan flooding are produced by using GIS to select bedrock/Quaternary alluvial fan contacts and Quaternary alluvial fan/undifferentiated Quaternary-age sediment contacts, and then combining the Quaternary alluvial fan units into a single alluvial fan unit (the "footprint"). Bedrock units are combined into a single non-alluvial fan-bedrock map unit. The axial valley deposits, including (among others) peralic, eolian, and stable channel fluvial deposits, are likewise combined to form a map unit depicting undifferentiated Quaternary sediments (See figures 3A through 3D). The primary concern is to show the alluvial fan footprint at 100k, as part of the AFTF Integrated Approach planning manual.

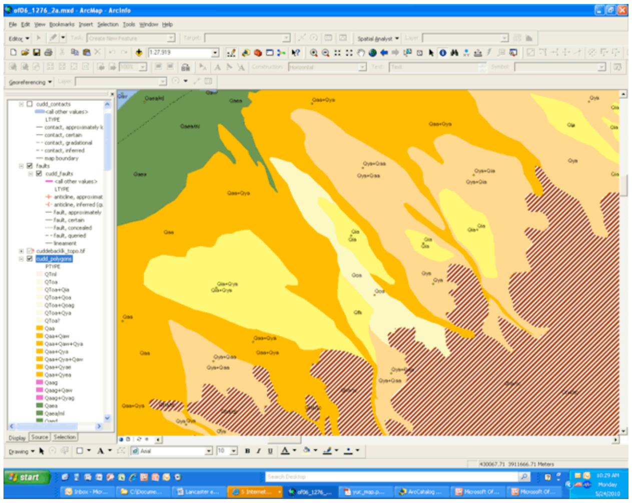

Figure 3A. Digital representation of the Surficial Geologic Map of the Cuddeback Lake 100k quadrangle (data taken from Amaroso and Miller, 2006). Green and blue colors represent Quaternary-age eolian and axial valley deposits; Orange, yellow and tan colors represent Quaternary-age alluvial fan deposits; red hatchured unit represents metamorphic bedrock.

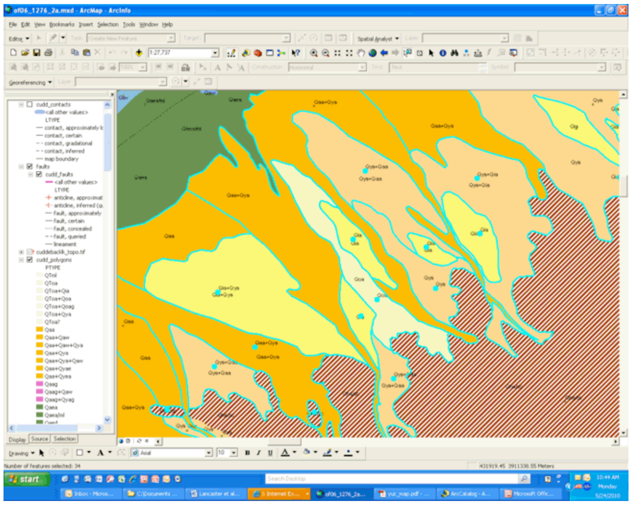

Figure 3B. Selection of all Quaternary-age alluvial fan units.

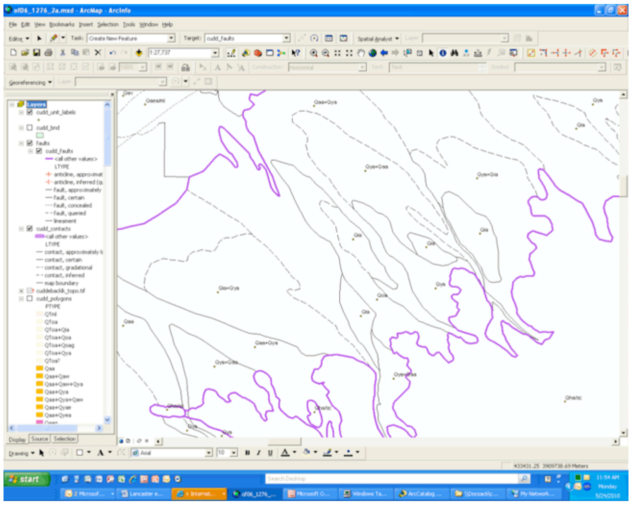

Figure 3C. Merged units (Quaternary-age alluvial fan unit shown between the purple lines).

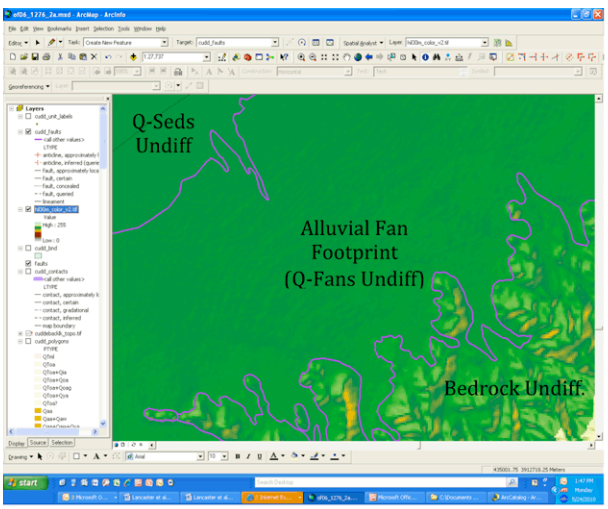

Figure 3D. Representation of the final derivative alluvial fan footprint advisory map showing bedrock, Quaternary-age alluvial fan, and undifferentiated Quaternary sediment polygons.

Digital Mapping of Alluvial Fan Footprint

Where digital information is not available for an individual 100k quadrangle, manual "heads-up" digitization at a screen scale of approximately 1:24,000 is necessary to complete the advisory map. The areas are mapped by observing alluvial fan geomorphic features and following National Research Council (NRC) and FEMA guidelines for identifying the presence of alluvial fans; these are:

Composition – Is the area underlain by Quaternary-age alluvium.

Morphology – Is the geomorphic expression of the landform fan-shaped on topographic maps or DEM.

Location – Is the landform located adjacent to a topographic break.

Digital data available for this type of mapping are many and varied; the most common sources are digital raster graphics (DRGs) such as 7.5-minute USGS topographic maps, 2005 and 2009 1-meter resolution NAIP imagery, and USGS 10-meter DEM (from the National Elevation Dataset). Variations to these data include slope and hillshade maps derived from DEM, and color infrared NAIP. These data provide a means to approximate both the bedrock/alluvial fan contact, and the alluvial fan/undifferentiated Quaternary-age sediment contacts.

DERIVING RELATIVE HAZARD INFORMATION FROM SURFICIAL GEOLOGIC MAPS AND SITE ASSESSMENTS

The Role of Surficial Geologic Maps In Assessing Alluvial Fan Flooding

Surficial geologic maps of alluvial fans provide a record of the long-term flooding history that are a function of tectonic processes, climate change, and various feedback mechanisms (Pelletier and others, 2005; and Bull, 2007). The use of surficial geologic maps and geomorphology in flood hazard analyses on alluvial fans was formally recognized by the National Research Council (NRC, 1996) and by FEMA in their Guidelines and Specifications for Mapping Partners (2003). FEMA guidelines must be followed in all cases, yet the areal extent of FEMA mapping on alluvial fans is limited to where there is community participation in NFIP.

Planning departments and developers, up to this time, have had little available map-based communication of the hazard on alluvial fans other than Flood Insurance Rate Maps (FIRM) that are not available for most undeveloped alluvial fan areas. To address these issues, the California Geological Survey has developed an engineering geologic approach for land use planning, using surficial geologic maps and site assessments to determine the general distribution of alluvial fans and the relative potential for alluvial fan flooding.

The Relative Potential Of Alluvial Fan Flooding

The recent work in Clark County Nevada, by House (2005, 2007) and Robbins and others (2008) identifies that the relative potential for alluvial fan flooding is a function of the age and geomorphic position of alluvial fan surfaces. Surficial geologic maps identify areas with flood and debris flow deposits of various ages, including modern drainage systems, their flow paths, and drainage divides (Robbins and others, 2008). As a part of the AFTF work products, CGS developed a similar approach to use surficial geologic maps to address the types and relative ages of alluvial fan deposits for preliminary assessment of the relative potential for alluvial fan flooding. CGS also identified additional information from site assessments, such as the potential for avulsion and debris flows, which should be considered in the assessment of alluvial fans. These preliminary studies may be conducted for pre-project assessment, or for entire fan regional planning. Based on this approach, surficial geologic maps coupled with site assessments may be used to develop a preliminary ranking of an area as:

> **Relatively High (for alluvial-fan flooding)** – Channels and washes (of latest Holocene-age, <500 years or so), debris flow hazard areas, or entire fan areas subject to historical and future migration of flow paths.
>
> **Relatively Moderate** – Alluvial fan terraces that are moderately incised and raised above surrounding latest Holocene -age channels and washes. These areas are considered to have a moderate hazard. Fan terrace surfaces that are narrow interfluves surrounded by, or interwoven with, latest Holocene-age channels should be included with the Relatively High areas.
>
> **Relatively Low** – Relict fans, or adjacent surfaces of deeply entrenched fan heads containing well-developed soils that are elevated above active washes.
>
> **Debris Flow Hazard Area** – Areas where Holocene-age debris flow deposits have been mapped based on geomorphic and geologic evidence, or where debris flows are anticipated.
>
> **Uncertain due to Disturbance** – Areas where disturbances to natural flow patterns have occurred, and so the relative hazard cannot be reliably mapped at or below the disturbed areas.

These relative hazards designations are illustrated on both an oblique aerial photograph of the north slope of the Santa Rosa Mountains near Travertine Point, Riverside County, California (figure 4) and a geomorphic profile using surficial geologic map designations (figure 5).

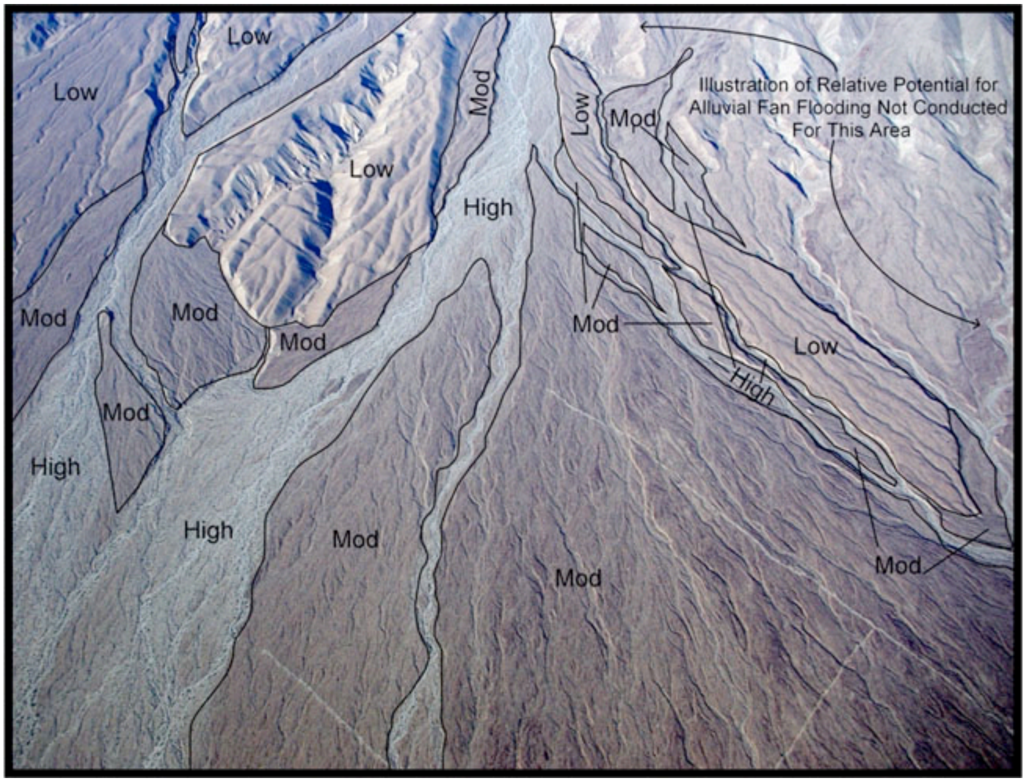

Figure 4. The relative hazard to alluvial fan flooding in the Santa Rosa Mountains, Riverside County, California. High areas include latest Holocene-age alluvial fan and wash deposits; moderate areas include Holocene-age abandoned alluvial fan surfaces with faint-to-strong desert varnish development; low areas are relict alluvial fan surfaces dissected with tributary drainage patterns.

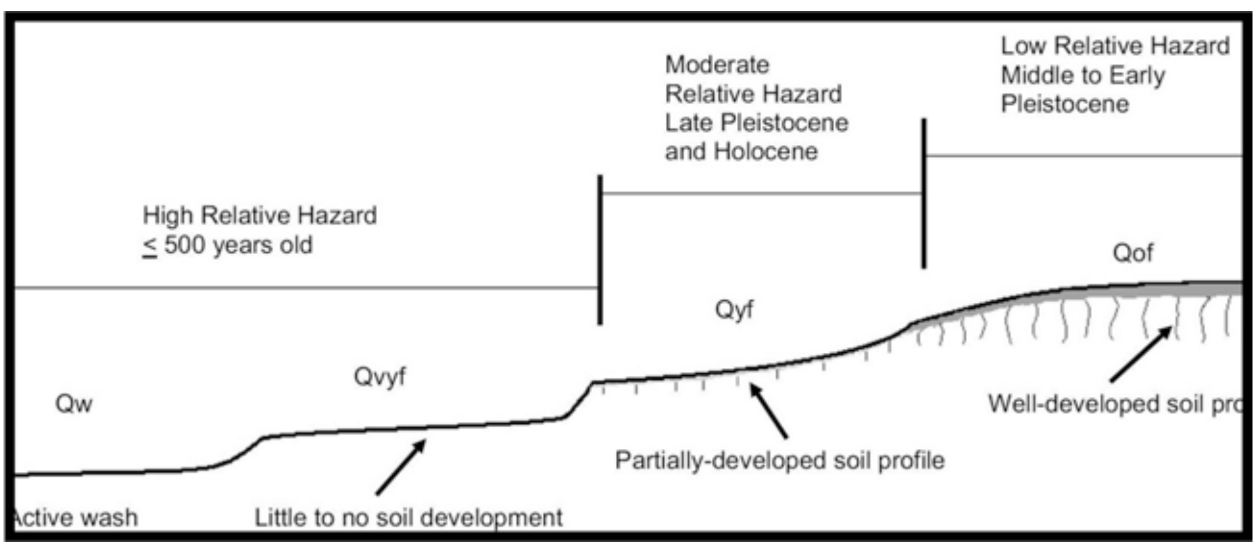

Figure 5. Illustrative geomorphic profile of the relative hazard to alluvial fan flooding. Surficial mapping nomenclature based on J. Matti and P. Cossette (USGS), in preparation.

Assessing the Potential for Debris Flow

The debris flow hazard on alluvial fans is a complex problem, and whereas quantitative site-specific studies may utilize probabilistic analyses, for planning purposes, identifying Holocene-age debris flow fans provides a preliminary indication of the susceptibility of areas where debris flow may occur (see figure 6). This is because Holocene-age debris flow deposition is indicative of active processes occurring under the current climate regime (Giraud, 2005).

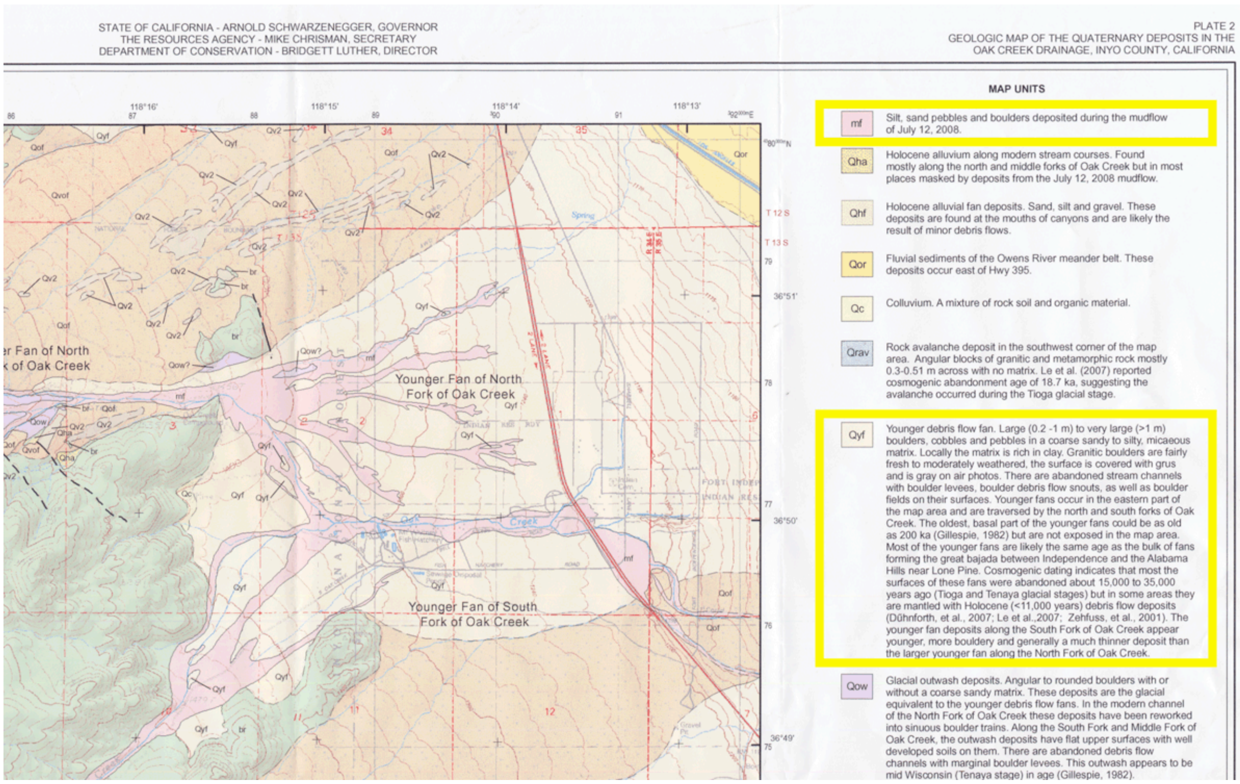

Figure 6. Draft Quaternary geologic map of the Oak Creek alluvial fan system (Wagner and DeRose, in press), showing the location of historical debris flow deposits, and the designation of Holocene-age debris flow deposits. Highlight boxes drawn around the mapped debris flow deposit of July 2008, and the mapped Holocene-age debris fan deposits.

For preliminary indication of the potential for debris flow on an alluvial fan, the focus of study should be to identify the dominant mode of alluvial deposition - stream flow, debris flow, or composite, and then to identify where debris flow deposition has occurred in the Holocene Epoch. From a long-term planning, or pre-project standpoint this information may then be used as the impetus for quantitative analysis of debris flow volumes during design phase analyses.

The geomorphic expression of debris flows has been documented by many workers in the field. Whipple and Dunne (1992) found that the roughness of alluvial fan surfaces dominated by debris flow processes is controlled by the viscosity of debris flows. Fan apices and proximal areas tend to contain rougher surfaces expressed as channels with boulder lined levees, terminal snouts and boulder fields, due to higher viscosity debris flows (see figure 7). Lower viscosity flows tend to smooth the lower fan surfaces by depositing less viscous debris further downfan in low-lying areas and channels.

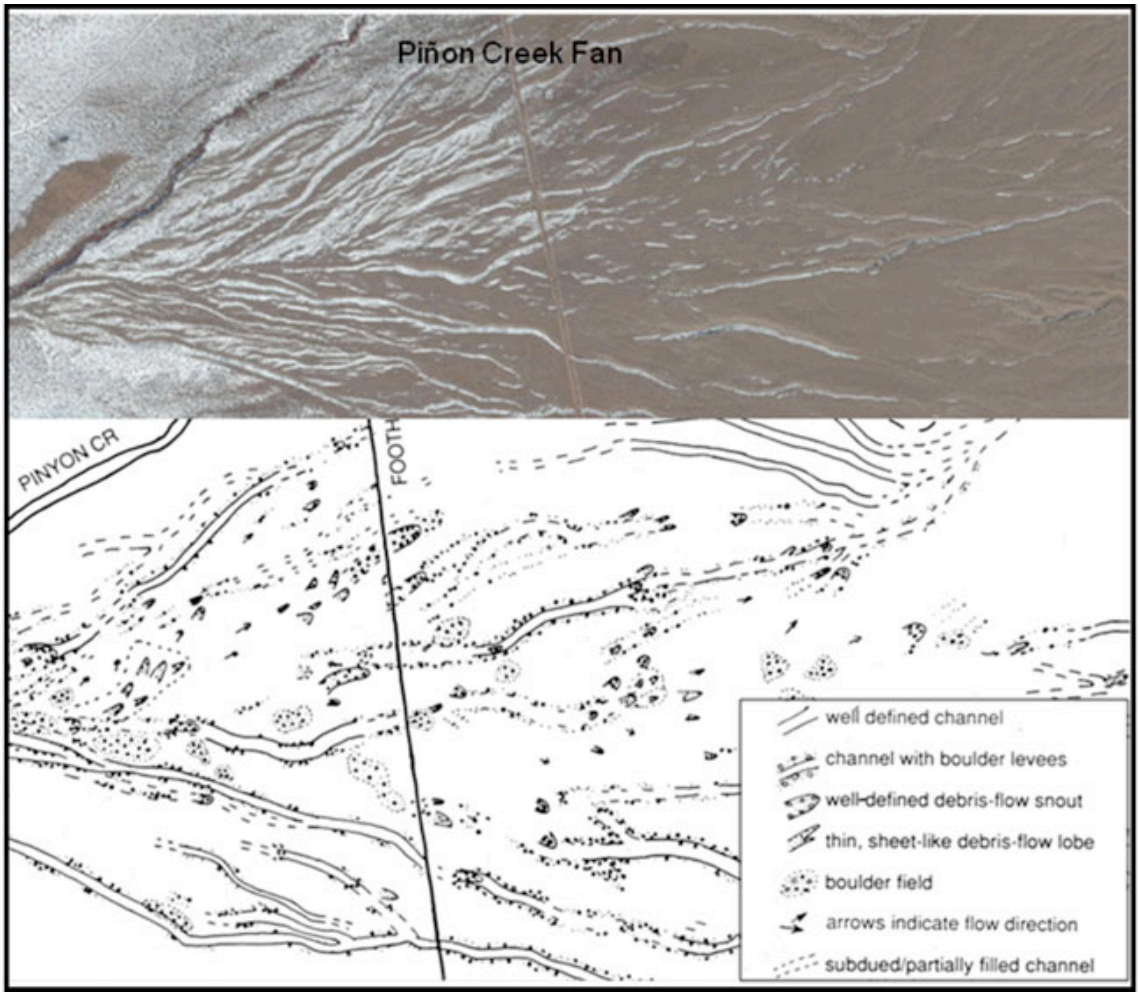

Figure 7. Upper part of figure shows NAIP aerial photograph of the Pinon creek debris flow fan. Lower part shows map depicting the character and location of debris flow features.

Assessing the Potential for Fluvial Avulsion

Fluvial avulsion may occur on alluvial fans that are dominated by water floods or flooding that is hyperconcentrated with sediment. They tend to occur at channel bends, where channels have high width-to-depth ratios (Field, 2001), and in areas that are aggrading, thereby causing channel bed elevations to increase relative to channel banks. They may also occur due to stream piracy, where overland flow causes incision and headward erosion into active channels, thus causing a redirection, or redistribution of flow on the fan. Figure 8 shows the process of avulsion via stream piracy.

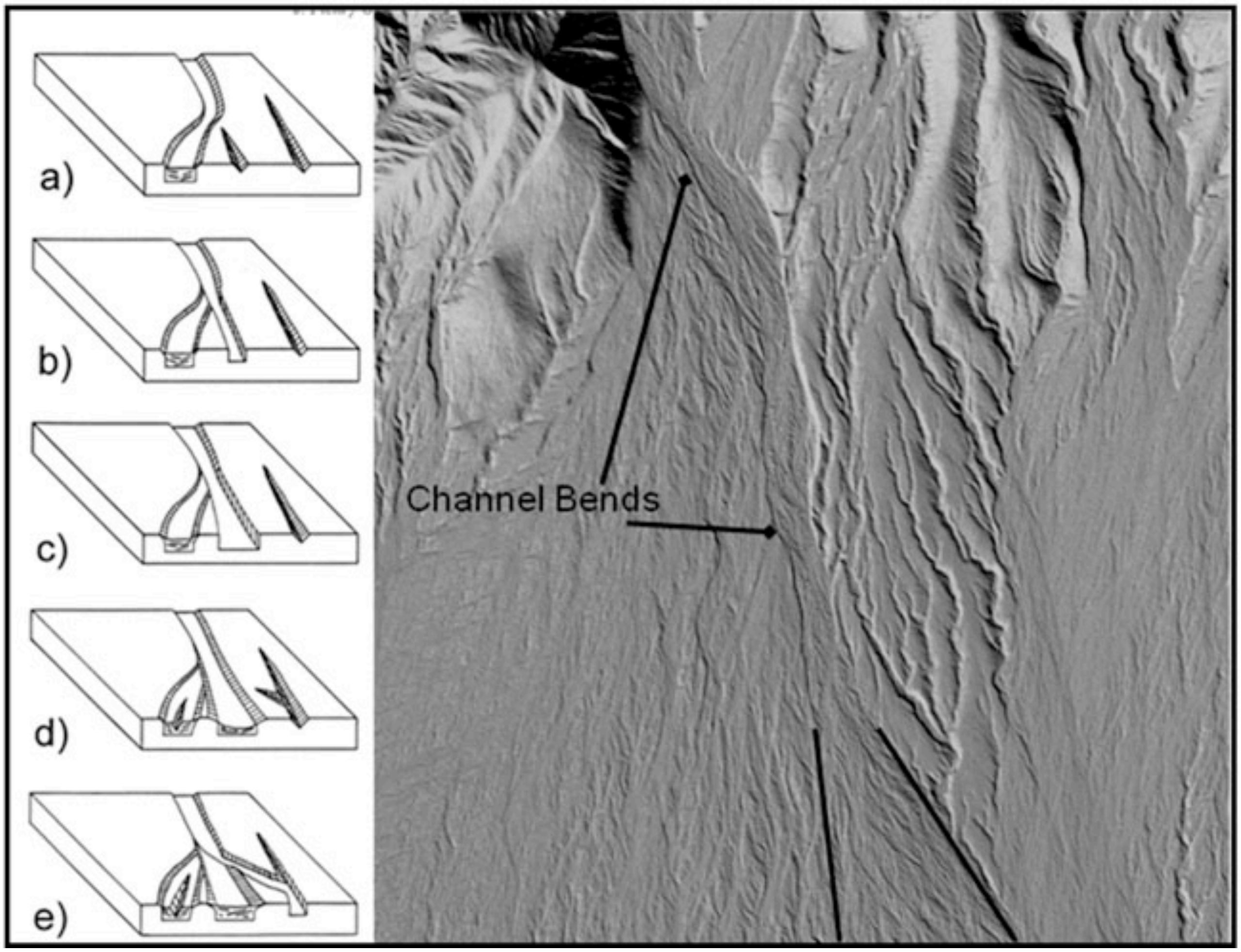

Figure 8. Left side of figure shows the channel processes that lead to fluvial avulsion on alluvial fans (from Field, 2001). Right side shows LiDAR shaded DEM illustrating channel bends, where avulsion may occur on alluvial fans.

Assessing the Potential for Debris Flow Avulsion

Alluvial fans that are dominated by debris flow processes commonly have incised channels due to more frequent (for example, annual event) fluvial erosion processes. These channels may lead an investigator to falsely conclude that the channels are stable and that, therefore, the hazard is low. However, these channels serve as pathways where debris flows may travel for a limited distance until the channels are overtaxed by the sheer volume of flow. As with fluvial avulsion, debris flow avulsion tends to occur at channel bends, but can occur much more frequently at the fan apex and proximal portions of the fan. Figure 9 shows a debris flow that occurred on an alluvial fan in Inyo County, CA.

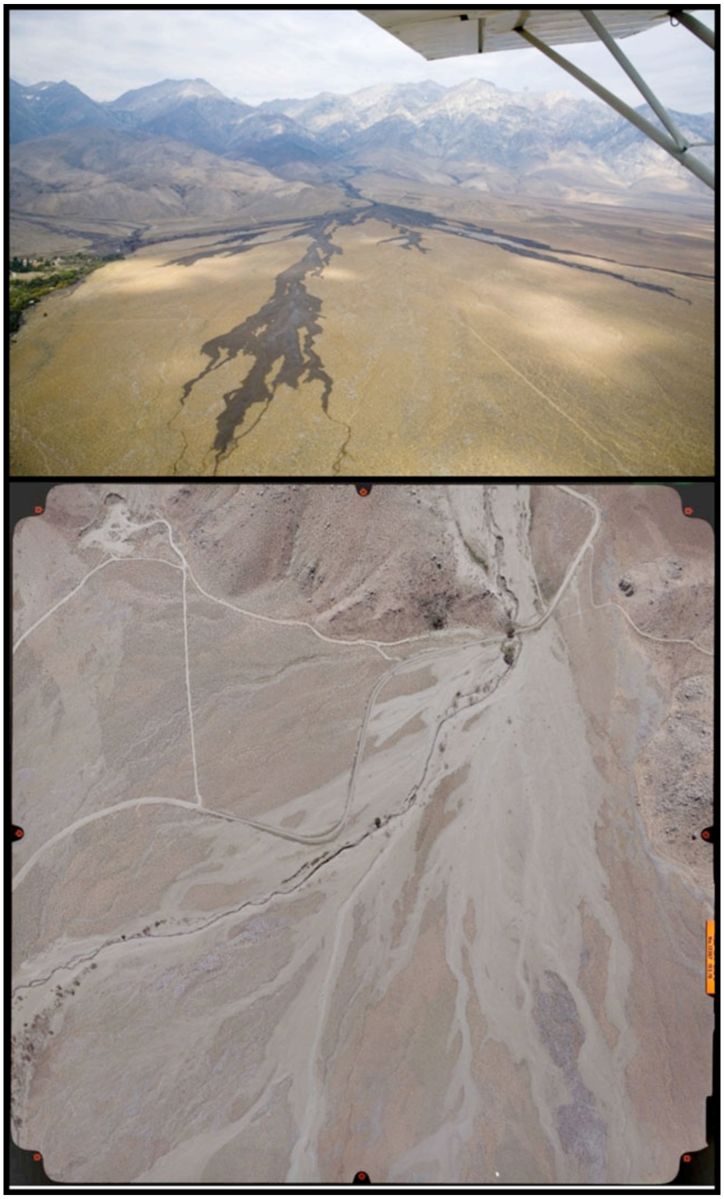

Figure 9. Upper part of figure shows oblique aerial photograph of debris flow on the Oak Creek alluvial fan, Inyo County, California (July, 2008, photograph by Ken Babion). Lower part shows aerial photograph of Oak Creek alluvial fan debris flow, weeks after the event, showing where the debris flow avulsions occurred at the channel bends (photograph by Caltrans, 2008).

Summarizing the Derivative Products

For land-use planning, alluvial fan footprint maps derived from digital geologic map data provide advisory information on general distribution of alluvial fans, and indicate where detailed studies of alluvial fan flooding potential may be necessary. Where proposed development sites are located within the Quaternary-age alluvial fan hazard areas, additional assessments of the relative hazard to alluvial fan flooding may be conducted by accessing digital geologic map data, analyzing the age and topographic position of geomorphic surfaces, and performing field assessments of the potential for avulsion and Holocene-age debris flow deposition. Following this approach, derivatives of geologic maps produced by CGS indicate the relative hazard to alluvial fan flooding as relatively low, relatively moderate, relatively high, and the designation of areas susceptible to debris flow (figure 10). These maps may be used by planners, developers, and homeowners to avoid development of hazardous areas and to design for proper flood and debris flow management facilities.

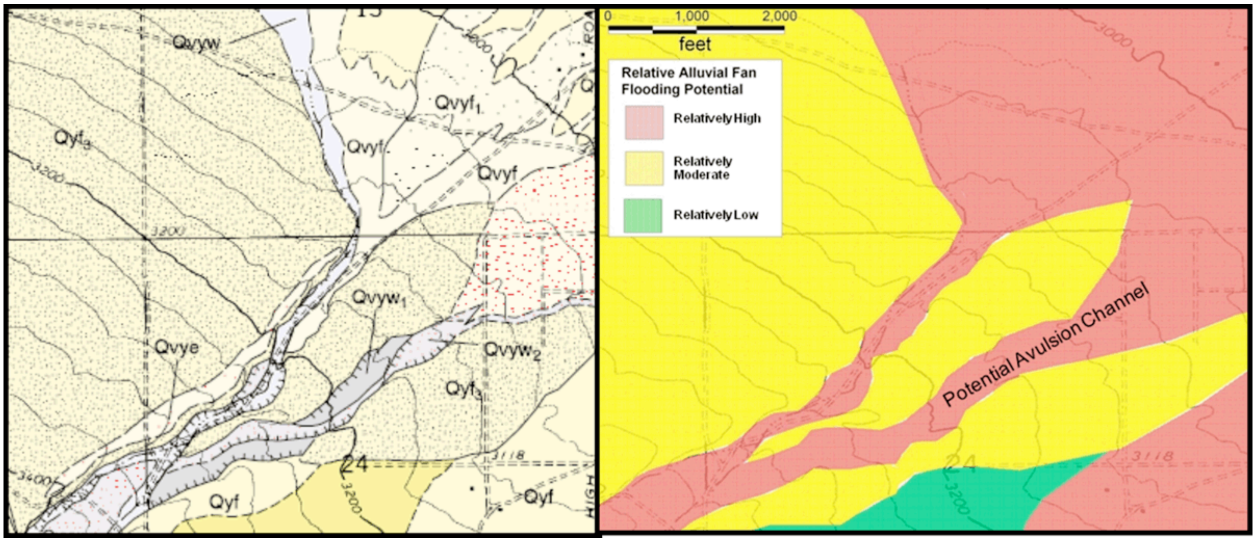

Figure 10. Left side of figure shows portion of the geologic map of the Fifteenmile Valley 7.5' quadrangle (Miller and Matti, 2001). Right side shows identification of relative alluvial fan flood hazard areas for the same area.

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